

Study of the performance of a large scale water-Cherenkov detector (MEMPHYS)

Luca Agostino,^a Margherita Buizza-Avanzini,^a Marcos Dracos,^b Dominique Duchesneau,^c Michela Marafini,^{a,0} Mauro Mezzetto,^d Luigi Mosca,^e Thomas Patzak,^a Alessandra Tonazzo^a and Nikolaos Vassilopoulos^{a,b}

^aAPC, Univ. Paris Diderot, CNRS/IN2P3, CEA/Irfu, Obs. de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France

^bIPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France

^cLAPP, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France

^dINFN Sezione di Padova, I-35131 Padova, Italy

^eLaboratoire Souterrain de Modane, F-73500 Modane, France

E-mail: tonazzo@in2p3.fr

Abstract. MEMPHYS (MEgaton Mass PHYSics) is a proposed large-scale water Cherenkov experiment to be performed deep underground. It is dedicated to nucleon decay searches, neutrinos from supernovae, solar and atmospheric neutrinos, as well as neutrinos from a future Super-Beam or Beta-Beam to measure the CP violating phase in the leptonic sector and the mass hierarchy. A full simulation of the detector has been performed to evaluate its performance for beam physics. The results are given in terms of “Migration Matrices” of reconstructed versus true neutrino energy, taking into account all the experimental effects.

ArXiv ePrint: [1206.6665](https://arxiv.org/abs/1206.6665)

⁰Currently at Università La Sapienza, Rome, Italy

Contents

1	Introduction	1
2	The MEMPHYS detector	1
3	MEMPHYS simulation and analysis	2
4	Migration Matrices	5
5	Conclusions	8

1 Introduction

A megaton-scale water Cherenkov detector would have competitive capabilities for accelerator-based neutrino oscillation physics. In addition, it would reach a sensitivity on the proton lifetime close to the predictions of most supersymmetric or higher dimension grand unified theories and it would explore neutrinos from supernovae and from other astrophysical sources.

Such a detector is most attractive because it relies on a well established technique, already used by the IMB [1], KamiokaNDE [2] and SuperKamiokande [3] experiments. Each tank will be roughly 10 times the size of SuperKamiokande, a reasonable extension of a known, well performing detector.

An expression of interest for such a project, called MEMPHYS (MEgaton Mass PHYSics), was prepared [4].

The potential for neutrino physics with specific Super-Beams and Beta-Beams at the Fréjus site was investigated in detail in [5]. The authors assumed the same performance as the SuperKamiokande detector in terms of detection efficiency, particle identification capabilities and background rejection. The behaviour of a larger scale detector will, however, be different, because of the larger distance travelled by light to reach the photomultipliers.

In this paper, a realistic evaluation of the expected MEMPHYS performance is presented. It is based on a full simulation and complete reconstruction and analysis algorithms. “Migration Matrices” from true to reconstructed neutrino energy are provided.

2 The MEMPHYS detector

MEMPHYS is a proposed large-scale water Cherenkov detector with a fiducial mass of the order of half a megaton.

The detector could be installed at the Fréjus site, near the existing *Laboratoire Souterrain de Modane* (LSM laboratory), in the tunnel connecting France to Italy, located at 130 km from CERN and with a rock overburden of 4800 m.w.e. Possible installation at other European sites was studied in the context of the LAGUNA EU-FP7 Design Study [6].

The original plan [4] envisaged 3 cylindrical detector modules of 65 meters in diameter and 60 meters in height. At the Fréjus site, the characteristics of the rock allow for a larger excavation in the vertical direction. Heights up to 103m are possible, which would allow for the same total fiducial mass with only two modules. The latest design [7] envisages 2 modules of 103m height and 65m diameter. Taking into account a 1.5m thick veto volume

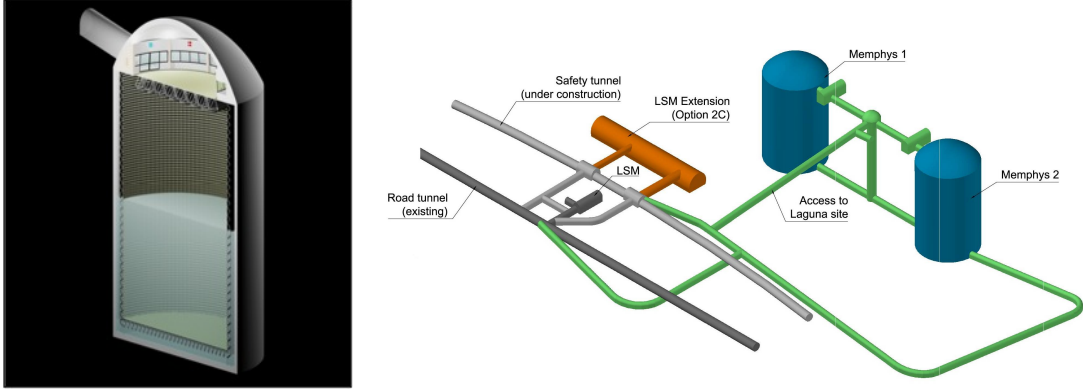


Figure 1. Schematic view of one MEMPHYS module (left) and design for installation and infrastructure at a possible extension of the LSM underground laboratory at the Fréjus site (right). Each tank is 65m in diameter and 103m in height. The total fiducial mass is 500 kton.

surrounding the main tank and a cut at 2m from the inner tank wall for the definition of the fiducial volume, as done in SuperKamiokande to allow for Cherenkov cone development, the total fiducial mass would be 500 kilotons.

Each module is equipped with ~ 120000 8" or 10" photomultipliers (PMTs) providing 30% optical coverage (equivalent, in terms of number of collected photoelectrons, to the 40% coverage with 20" PMTs of SuperKamiokande).

A schematic view of the detector and of a possible layout for installation at the Fréjus site are shown in figure 1.¹

3 MEMPHYS simulation and analysis

In order to evaluate realistic performance for the above-described baseline detector, a detailed simulation has been developed, mainly in the context of the EUROnu FP7 Design Study [8]. The code, based on the Geant-4 toolkit [9, 10], was originally written for the T2K-2km detector [11], then interfaced with the OpenScientist framework [12]. It allows for interactive event viewing, batch processing and analysis. Special care has been devoted to the modularity of the code in the definition of the detector geometry, to facilitate future detector optimisation studies. The GENIE [13] event generator is used for neutrino interactions.

One basic quantity used to evaluate the detector performance is the number of photoelectrons (PEs) as a function of the particle energy. This is shown in figure 2 (left), for electrons generated uniformly in the detector volume. The number of PEs per MeV is about constant and equal to 11 for energies above 5 MeV. Figure 2 (right) shows the number of hit PMTs as a function of energy.

These quantities were verified to be stable with respect to the tank height, thus this parameter has no impact on the detector's performance. The new baseline configuration, with 2 tanks of 65m diameter and 103m height, is used in the following.

A complete analysis chain has been developed, based on what is done in SuperKamiokande (SK) [14]. Some of the algorithms are a simplified version of the SK ones. Their performance

¹Courtesy of Lombardi Engineering S.A.

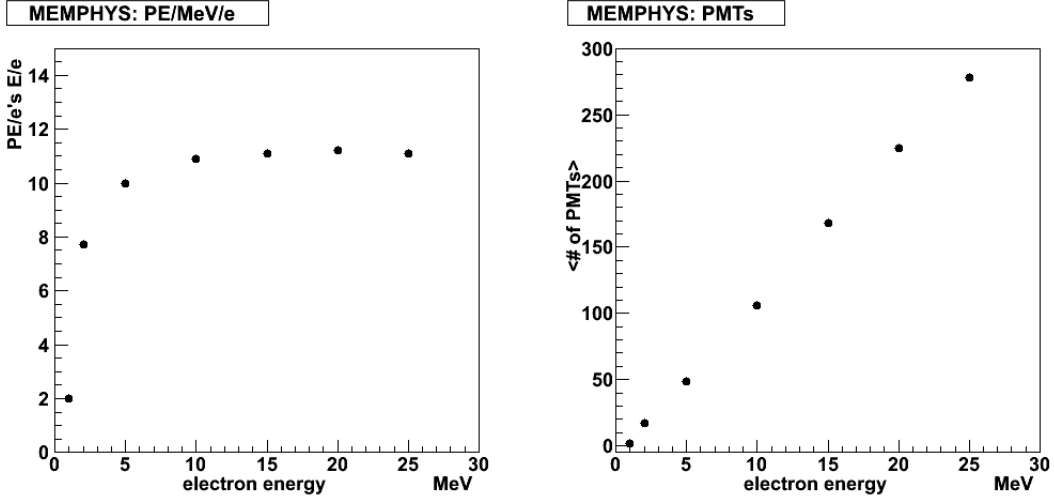


Figure 2. Left: Number of detected photoelectrons per MeV as a function of electron energy. Right: Number of PMTs with at least one photoelectron as a function of electron energy.

was also evaluated by running the full simulation with the SK parameters (size, PMT coverage etc.) to ensure that no significant degradation of efficiencies and background rejection are introduced by our algorithms.

The aim of the analysis is the reconstruction of the incoming neutrino energy and the identification of its flavour, to perform appearance or disappearance analyses with the different types of beams. This is only relevant for Charged Current (CC) neutrino interactions. Neutral Current (NC) interactions where a final-state pion can mimic an electron or muon are considered separately.

The analysis proceeds through the following steps:

- reconstruction of the interaction vertex, from the timing of the hits in the different PMTs;
- determination of the outgoing lepton direction, from the pattern of the Cherenkov ring;
- lepton identification, from the “fuzziness” of the Cherenkov ring: since electrons are more subject to bremsstrahlung and multiple scattering, they produce rings which are less “sharp” than the ones from muons; A simplified particle identification algorithm is used, considering the fraction of charge inside the edge of the ring;
- rejection of NC interaction with a π^0 in the final state, by transforming rings into peaks with a Hough transform [15] and counting the number of peaks;
- reconstruction of the lepton momentum, from the measured charge in the PMTs.

Figure 3 shows examples of a single-ring (electron) and a double-ring (π^0) event: the rings are first projected in spherical coordinates centered on the fitted particle vertex and direction, then Hough-transformed to peaks. The π^0 identification algorithm used in this analysis is much simplified with respect to the one used in SK and in the HyperKamiokande LOI [16] and we don’t implement a cut on the invariant mass of two rings, when a second ring is forced to be found. The efficiencies of this particular cut were thus rescaled to the ones

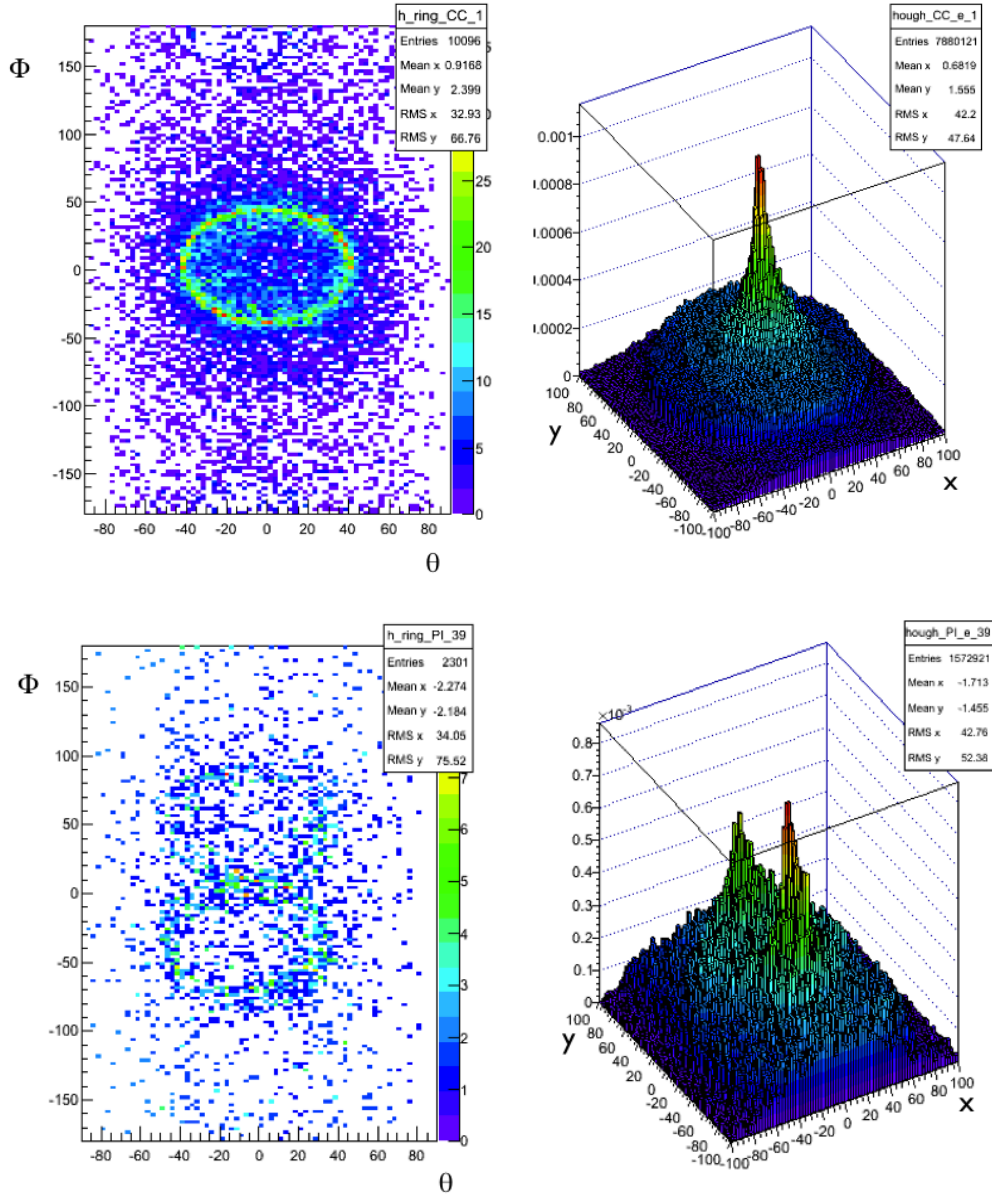


Figure 3. Single ring (top) and double ring (bottom) events: projection in spherical coordinates centered on the reconstructed vertex and direction (left) and their Hough transform (right).

of [16], under the assumption that we will eventually implement their full likelihood analysis and cuts. The efficiencies were also rescaled to take into account the implementation of a cut on the Michel electron from muon decay; this cut introduces some differences between muon neutrino and anti-neutrino identification efficiency, and in addition suppresses completely the ν_e contamination in the ν_μ sample.

The incident neutrino energy is deduced from the measured lepton momentum and direction, assuming the interaction to be CC and quasi-elastic (QE). In a pure 2-body collision $\nu_l + N \rightarrow l + N'$ (where $l=e$ or μ and N denotes a nucleon, either p or n), and assuming the

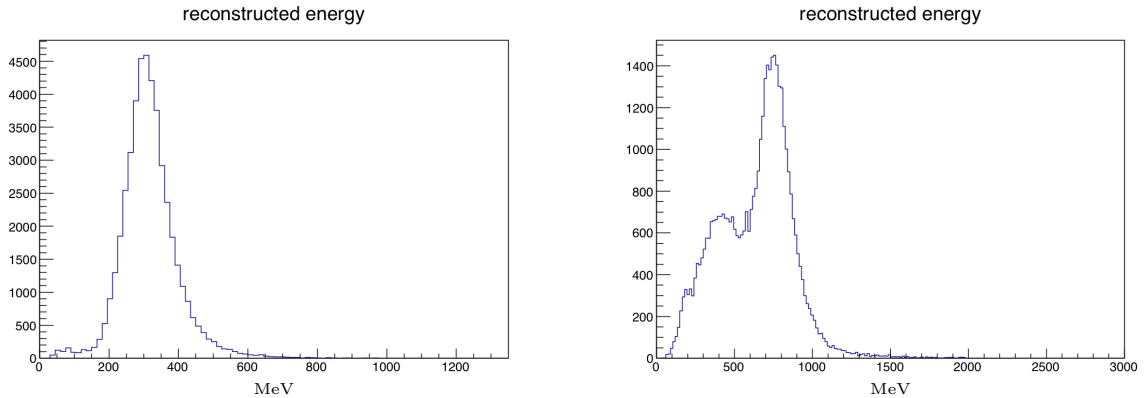


Figure 4. Reconstructed energy for selected muon neutrinos with energies of 360 MeV (left) and 840 MeV (right).

nucleon is at rest, the incoming neutrino energy E_ν is related by simple kinematics to the outgoing lepton energy E_l and momentum P_l and to the angle θ_l of the lepton direction with respect to the neutrino:

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + P_l \cos \theta_l} \quad (3.1)$$

The difference between the reconstructed and true neutrino energy in two different energy ranges is shown in figure 4: the Gaussian peak is due to true QE interactions, with a smearing induced by the Fermi motion of the nucleon and the experimental resolution, while the tail at lower reconstructed energies is due to non-QE interactions, whose contribution is larger as energy increases.

4 Migration Matrices

In order to properly take into account all the effects of the reconstruction, the detector performance is conventionally described in terms of “Migration Matrices” representing the neutrino reconstructed energy versus the true one. Each “slice” of true energy is normalized such that the projection of the matrix corresponds to the efficiency for the given neutrino energy. Separate matrices are constructed for signal and background in the different detection channels, and for CC and NC events.

Events identified as electron neutrinos represent the signal in the appearance channel in a “traditional” neutrino beam (Super-Beam) [17], composed mainly of ν_μ ’s, where the oscillation $\nu_\mu \rightarrow \nu_e$ is searched. Separate migration matrices are provided from CC and NC interactions. The background is represented by mis-identified ν_μ CC interactions as well as by other components present in the beam in small fraction (mainly ν_e ’s and anti-neutrinos; no detailed study has been performed here for ν_τ ’s, since the beam energy is below the threshold for τ production). Events identified as muons are the signal for the appearance channel $\nu_e \rightarrow \nu_\mu$ with a Beta-Beam [18, 19] or for the disappearance channel $\nu_\mu \rightarrow \nu_\mu$ with a Super-Beam.

The details of the matrices are provided in figure 5. The efficiencies as a function of neutrino energy are shown in figure 6.

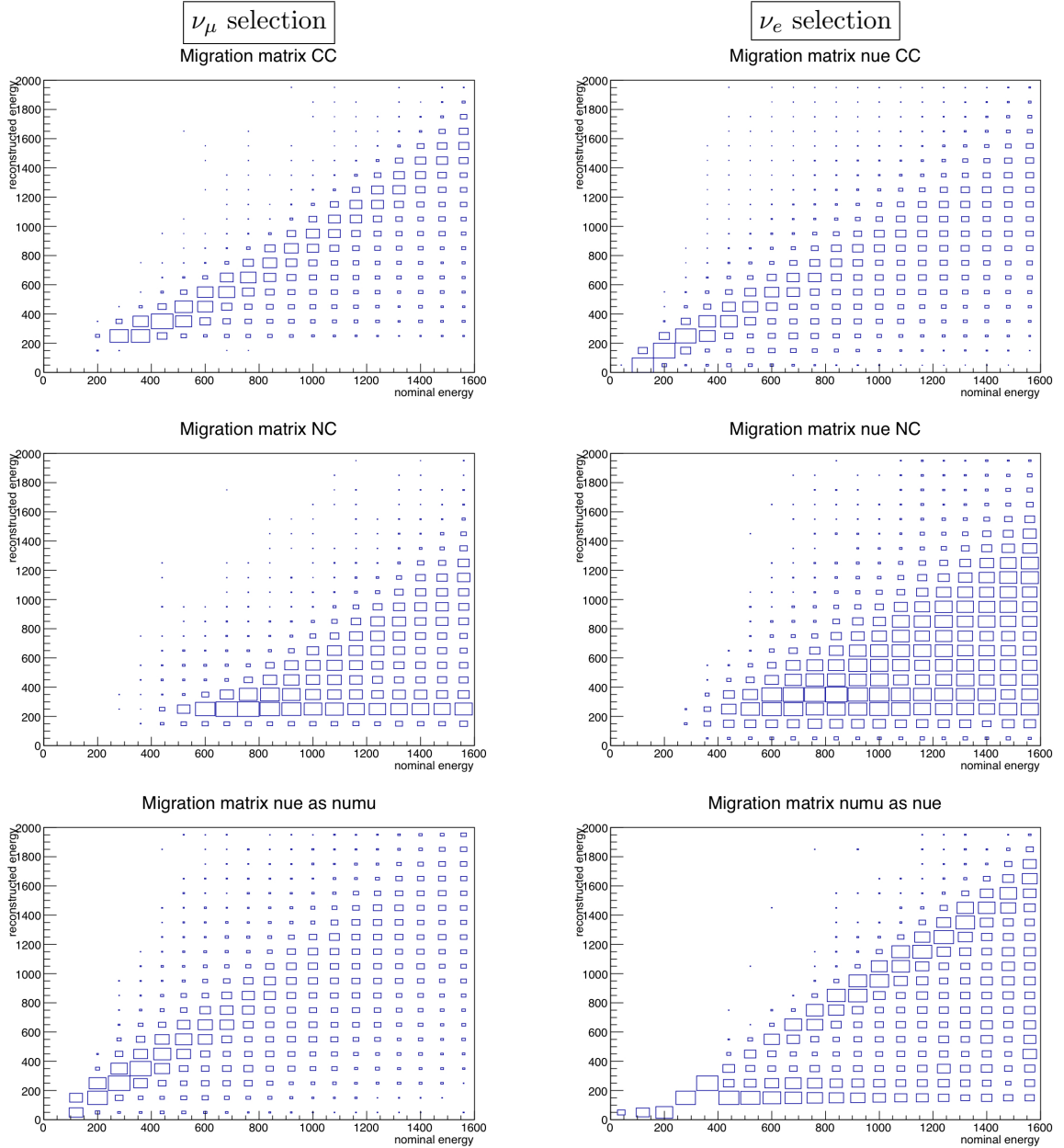


Figure 5. “Migration Matrices” with reconstructed neutrino energy as a function of true energy for selected events. Left: events identified as muon neutrinos, when they are ν_μ CC interactions (top), NC interactions (middle), ν_e CC interactions (bottom). Right: events identified as electrons, when they are ν_e CC interactions (top), NC interactions (middle), ν_μ CC interactions (bottom).

The matrices are available from the authors in the text format suitable as input for the GLOBES package [20, 21].

Figure 7 shows an example of study of sensitivity to the leptonic CP violation phase using the GLOBES package, with a Beta-Beam [5] and a Super-Beam [17] from CERN to the Fréjus site. For the Beta-Beam, a running time of 5 years with neutrinos and 5 years with antineutrinos is considered, with a systematic uncertainty of 2% on both signal and

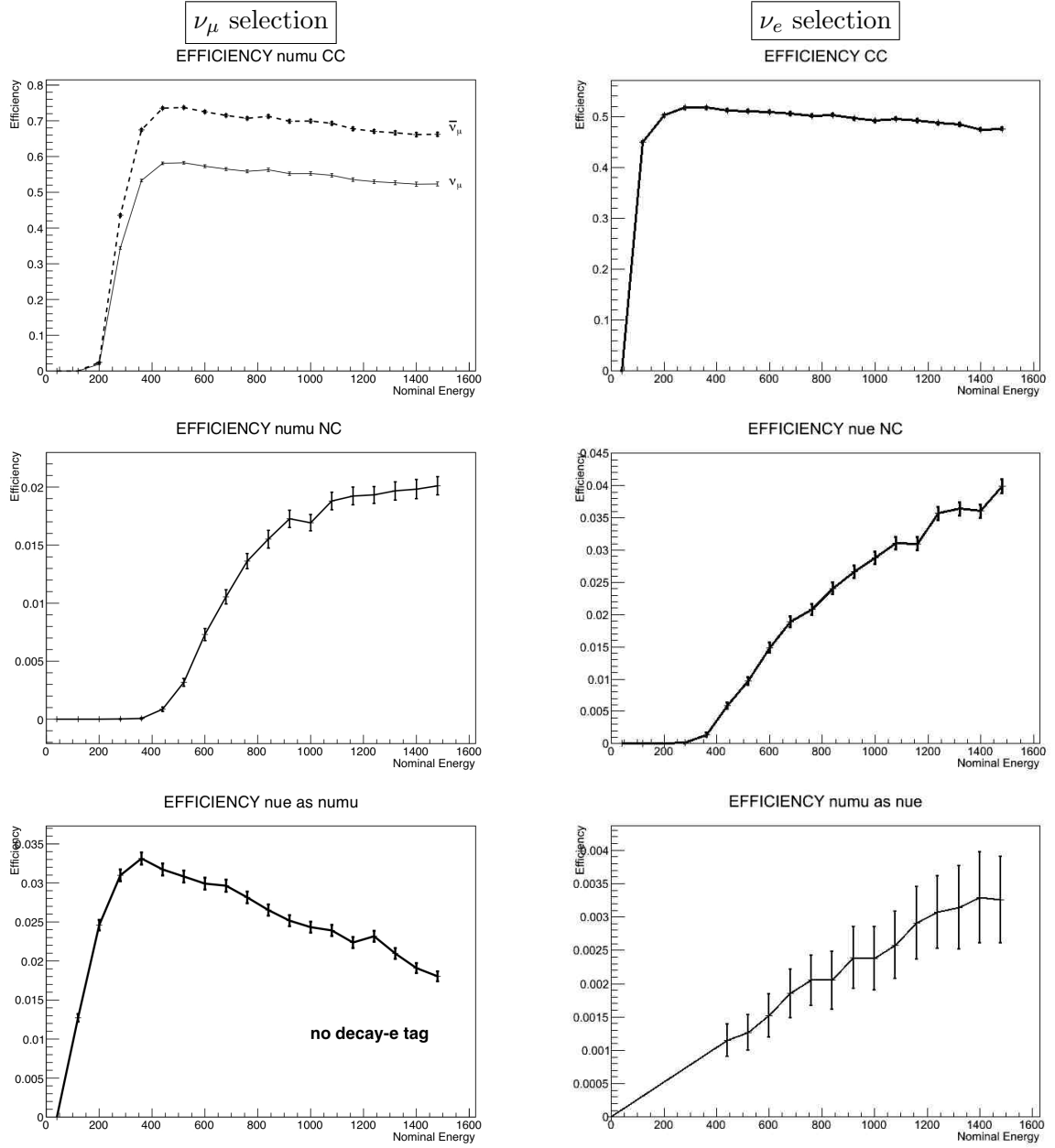


Figure 6. Efficiencies for the selection of the different neutrino event categories in the MEMPHYS detector, as a function of neutrino energy. Left: events identified as muon neutrinos, when they are ν_μ CC interactions (top), NC interactions (middle), ν_e CC interactions (bottom. The cut decay-electron tag completely suppresses ν_e CC interactions and has not been applied for this plot). Right: events identified as electrons, when they are ν_e CC interactions (top), NC interactions (middle), ν_μ CC interactions (bottom).

background. For the Super-Beam, a running time of 2 years with neutrinos and 8 years with antineutrinos is considered, with a systematic uncertainty of 5% on signal and 10% on background. Normal mass hierarchy is assumed. The sensitivity to the CP violation phase in the leptonic sector, δ_{CP} , is shown, at 3σ and 5σ , as a function of the θ_{13} mixing angle.

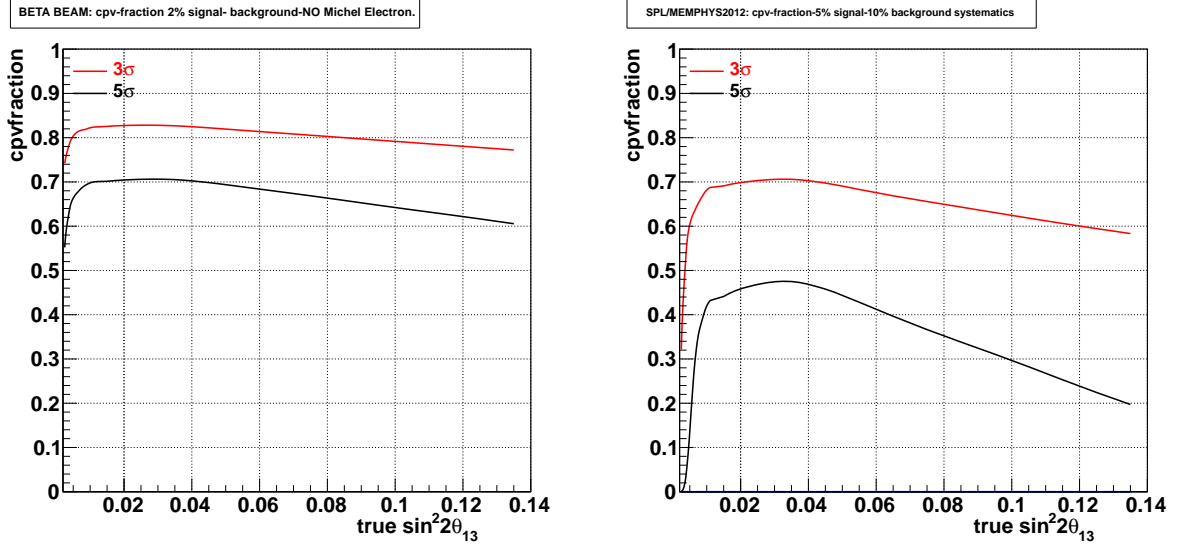


Figure 7. Example of study of sensitivity to the leptonic CP violation phase using the GLOBES package, considering a Beta-Beam (left) or a Super-Beam (right) from CERN to the Fréjus site.

5 Conclusions

A detailed study of the performance of a future large-scale water-Cherenkov detector, MEMPHYS, has been performed, using a full simulation of the detector’s response and realistic analysis algorithms. The results have been presented in terms of Migration Matrices from true to reconstructed neutrino energy, considering the signal and background channels for different neutrino beam types.

Acknowledgments

We are grateful to Enrique Fernandez Martinez for useful discussion. We acknowledge the financial support of the European Community under the European Commission Framework Programme 7 Design Study EUROnu, Project Number 212372 and Design Study LAGUNA-LBNO, Project Number 284518. The EC is not liable for any use that may be made of the information contained herein.

References

- [1] **IMB** Collaboration, C. Bratton et al. *Phys. Rev. D* **37** (1988) 3361.
- [2] **KamiokaNDE** Collaboration, M. Koshiba et al. *Nuovo Cim.* **C9** (1986) 141–158.
- [3] **Super-Kamiokande** Collaboration, S. Fukuda et al. *Nucl. Instrum. Meth.* **A501** (2003) 418.
- [4] A. de Bellefon, J. Bouchez, J. Busto, J.-E. Campagne, C. Cavata, et al., *MEMPHYS: A Large scale water Cerenkov detector at Frejus*, [hep-ex/0607026](https://arxiv.org/abs/hep-ex/0607026).
- [5] J.-E. Campagne, M. Maltoni, M. Mezzetto, and T. Schwetz, *Physics potential of the CERN-MEMPHYS neutrino oscillation project*, *JHEP* **0704** (2007) 003, [[hep-ph/0603172](https://arxiv.org/abs/hep-ph/0603172)].
- [6] **LAGUNA** Collaboration, T. Patzak et al., *LAGUNA: Future megaton detectors in europe*, *J.Phys.Conf.Ser.* **309** (2011) 012022.

- [7] J. Borne, J. Busto, J. Campagne, M. Dracos, C. Cavata, et al., *The MEMPHYS project*, *Nucl.Instrum.Meth.* **A639** (2011) 287–289.
- [8] <http://www.euronu.org/>.
- [9] **GEANT4** Collaboration, S. Agostinelli et al., *GEANT4: A Simulation toolkit*, *Nucl.Instrum.Meth.* **A506** (2003) 250–303.
- [10] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Dubois, et al., *Geant4 developments and applications*, *IEEE Trans.Nucl.Sci.* **53** (2006) 270.
- [11] M. Fechner. personal communication, 2007.
- [12] G. Barrand. personal communication, 2007.
- [13] C. Andreopoulos, A. Bell, D. Bhattacharya, F. Cavanna, J. Dobson, et al., *The GENIE Neutrino Monte Carlo Generator*, *Nucl.Instrum.Meth.* **A614** (2010) 87–104, [[arXiv:0905.2517](https://arxiv.org/abs/0905.2517)].
- [14] **Super-Kamiokande** Collaboration, M. Shiozawa, *Reconstruction algorithms in the Super-Kamiokande large water Cherenkov detector*, *Nucl.Instrum.Meth.* **A433** (1999) 240–246.
- [15] E. R. Davies, *Machine Vision: Theory, Algorithms, Practicalities*. Academic Press, San Diego, 1997.
- [16] K. Abe, T. Abe, H. Aihara, Y. Fukuda, Y. Hayato, et al., *Letter of Intent: The Hyper-Kamiokande Experiment — Detector Design and Physics Potential —*, [[arXiv:1109.3262](https://arxiv.org/abs/1109.3262)].
- [17] A. Longhin, *A new design for the CERN-Fréjus neutrino Super Beam*, *Eur.Phys.J.* **C71** (2011) 1745, [[arXiv:1106.1096](https://arxiv.org/abs/1106.1096)].
- [18] P. Zucchelli, *A novel concept for a anti- ν_e / ν_e neutrino factory: The beta beam*, *Phys.Lett.* **B532** (2002) 166–172.
- [19] M. Lindroos and M. Mezzetto, *Beta Beams*. Imperial College Press, 2010.
- [20] P. Huber, M. Lindner, and W. Winter, *Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)*, *Comput.Phys.Commun.* **167** (2005) 195, [[hep-ph/0407333](https://arxiv.org/abs/hep-ph/0407333)].
- [21] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, *New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator*, *Comput.Phys.Commun.* **177** (2007) 432–438, [[hep-ph/0701187](https://arxiv.org/abs/hep-ph/0701187)].